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Kinematics of the New Zealand Plate Boundary: Relative Motion by GPS Across Networks of 1000 km and 50 km Spacing

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Measurements

The Christchurch to Hokitika GPS network, consisting of about 70 ground marks across the Australian-Pacific plate boundary zone in the South Island of New Zealand, has been measured three times during the course of this project. In addition, two post-earthquake surveys within the network have been completed.

The network was established in December 1992 [Williams, 1993; Pearson et al., 1995] and consists of measurements at the stations of the 1978 Christchurch-Hokitika triangulation/ trilateration network, a number of roadside benchmarks, and a few points newly established in 1992.

The network was partially reoccupied in July 1994 following the M_W 6.7 June 1994 Arthur's Pass earthquake which occurred in the middle of the network [Arnadottir et al., 1995; Robinson et al., 1995; Arnadottir, 1995; Abercrombie et al., 1998].

The network was completely remeasured in February 1995, then again in January 1997. In addition a one-day survey of 11 points was carried out in February 1996 to measure coseismic displacement due to the M_W 6.2 November 1995 Cass earthquake [Gledhill et al., 1998].

In both 1995 and 1997 a number of new points were added to the network. These were intended to fill gaps in the geographic coverage, and to provide a concentration of data in the vicinity of the intersection of the Hope and Alpine faults.

The 1992 and 1995 surveys have been described in earlier reports. During the 1997 survey - fourteen days from 10-23 January - we collected 4404 hours of useful GPS data (with "tails" before 00:00 UT and after 24:00 UT removed) in 224 individual sessions from 100 stations. With a maximum of about 6000 receiver hours attainable (after allowing for malfunctioning receivers) our receiver utilisation rate was about 74%. The fieldwork for the 1997 survey is described in more detail by Beavan [1997].

Data Archiving

Raw and rinex data and field logsheets from all these campaigns have been submitted to the UNAVCO archive. They are also on file at the Institute of Geological and Nuclear Sciences in Lower Hutt, New Zealand.

Data Analysis

The GPS data from all the surveys have been processed, or reprocessed in the case of the earlier data sets. Highlights of the GPS processing are:

- Bernese version 4.0 software [Rothacher et al., 1993; Rothacher and Mervart, 1996].
- Single differences formed in such a way as to minimise baseline lengths and reduce antenna mixing between ends of baselines.
- IGS_01 elevation-dependent antenna phase center models [Rothacher and Mader, 1996] used in all analyses.
- Tropospheric estimates made every 2 hours.
- UNAVCO graphics tool, gt, used in many cases to visually scan double-difference phase residuals for cycle slips, and occasionally to delete noisy data at low elevation angles.
- Double-differenced phase ambiguities estimated at both L1 and L2 frequencies. Ambiguities fixed to integer values, where possible, using wide-lane/narrow-lane technique.
- Ionospheric models estimated to assist with ambiguity resolution on longer baselines.
- Coordinate and covariance files are produced from a network solution of each observation session.

We use variation of coordinates program ADJCOORD [Bibby, 1982; Crook, 1992] to combine these daily coordinate and covariance files to generate a "static" solution for each campaign. This solution is used to estimate a covariance scaling factor from the scatter in repeated observations, and to identify outliers in the daily coordinate estimates.

We then combine the daily coordinate and covariance estimates from different observation years (again using ADJCOORD) to simultaneously estimate both coordinates and velocities/ displacements of the stations. We use the covariance scalings estimated in the previous step.

Results

From the 1995-97 data we are able to estimate interseismic velocities - the original aim of the project - though corrections must first be made for the coseismic effects of the Cass earthquake and postseismic effects of the Arthur's Pass event.

In the following, we present four sets of results:

- Interseismic velocities
- Arthur's Pass earthquake - coseismic
- Cass earthquake
- Arthur's Pass earthquake - postseismic

Work on all these fronts is still incomplete, but is being actively continued with funding from the NZ Foundation for Research, Science and Technology (FRST).

Interseismic velocities

Figure 1 shows 1995-97 interseismic velocities in map view and in cross section. The Cass coseismic and Arthur's Pass postseismic effects have been treated crudely by omitting from the map (Fig. 1a) all stations that were significantly affected by these two sources. However,

these effects have been retained in the cross section plot (Fig. 1b). The Cass displacements are large but are in a geographically restricted region along the NE edge of the network (see Fig. 4). The Arthur's Pass postseismic displacement is a more subtle feature.

A clear result is that all stations west of both the Alpine and Hope faults are hardly moving with respect to each other. The locus of the major contemporary deformation is well SE of both these faults, and appears to be further SE than in the 1978-92 deformation pattern analysed by Pearson et al. [1995] and Bourne [1996]. The fact that the locus of deformation remains well east of the Hope fault suggests that this fault, at least at its southern end, must be dipping towards the SE in the same way that the Alpine fault dips SE to the south of the Alpine-Hope fault intersection.

Arthur's Pass coseismic effects

GPS data, together with a partial analysis of the aftershocks of the 1994 Mw 6.7 Arthurs Pass earthquake, suggested that this earthquake was in large part a left-lateral "cross-fault", similar to the many left-lateral cross-faults in southern California, and the first well-documented such event in New Zealand [Robinson et al., 1995; Arnadottir et al., 1995]. The addition of the 1995 GPS data [Arnadottir, 1995] supports this model as the most likely interpretation of the earthquake based on geodetic data alone, if only one fault plane is allowed. However, body-wave and surface-wave inversions have suggested a rather simple pure-thrusting event, and preliminary interferometric synthetic aperture radar results [Pearson et al., 1997] also suggest a thrust rather than a strike-slip mechanism. Work is ongoing to reconcile these apparently incompatible results, and provides an example of how geodetic and seismological studies must work side by side to obtain the fullest understanding of earthquake sources [Abercrombie et al., 1998]. In the case of the Arthur's Pass earthquake, which occurred within a zone of transition between a predominantly strike-slip regime to the north and a largely continental collision regime to the south, the correct interpretation of the quake will be of great importance to our understanding of this transition zone and of the mechanisms responsible for the uplift of the Southern Alps.

The original inversion of the geodetic data gave the best fitting fault as a cross fault with a mix of left-lateral and thrust motion. It was necessary to make the amount of slip on the northern one-third of the fault plane (nearer to the epicenter) almost an order of magnitude larger than on the southern two-thirds (e.g., Fig. 2). There were indications that a model with two separate faults would provide a better fit, but there were insufficient data from the 1994 survey to confirm this [Arnadottir et al., 1995].

For the geodetic and seismic results to be consistent, it is clear that more than one fault must have been activated at the time of the earthquake or in the following two weeks (i.e., prior to the GPS resurvey). A working hypothesis is that the main shock was a more-or-less pure thrust as required by the various seismic inversions, and that two large aftershocks to the south were predominantly strike slip.

With the addition of the 1995 GPS data, there are about 20 points in the near-field of the earthquake, still not sufficient to reliably constrain a full two-fault inversion, since each fault requires nine parameters to describe it. Therefore, as well as confirming the one-fault inversion (Figure 2), Arnadottir [1995] performed a two-fault inversion with the strike, dip and rake of one fault constrained to those of the 3 km depth body-wave modeling solution

(strike, dip and rake 213°, 47° and 90°, respectively), and all the other parameters allowed to vary (Figure 3). The best-fitting model with these constraints has the second fault very similar to the southern part of the single-fault model, with almost pure sinistral motion. This is consistent with the focal mechanism of the largest aftershocks. However, the GPS model has a combined moment of 1.9×10^{19} Nm, with the two faults contributing approximately half each. This is incompatible with the 6:1 seismic moment ratio between the mainshock and largest aftershocks, and has lead to speculation that significant aseismic slip may be required in the south. The discrepancy between the seismic and geodetic results has still not been fully resolved [Abercrombie et al., 1998].

Since the work of Arnadottir et al. [1995] and Arnadottir [1995], we have reanalysed the 1992, 1994 and 1995 GPS data, and have collected and analysed data from 1997. The 1995-1997 data allow us to estimate an interseismic deformation correction from the GPS data. The new analyses and corrections do not significantly alter the coseismic data inverted in the two Arnadottir studies. However, there is evidence of postseismic deformation in the 1995-97 data in the region at the northwestern edge of the aftershock zone, which adds to evidence from the seismological inversions [Abercrombie et al., 1998] that the mainshock rupture plane dips to the northwest.

The coseismic deformation patterns estimated from the 1992-1994 and 1992-1995 data are very similar. We have performed forward dislocation modeling on both sets of data in a spirit similar to that of Arnadottir [1995]. Arnadottir searched rigorously for the best fitting two-fault model with the mainshock fault constrained to have the strike, dip and rake estimated from body wave modeling. We allow the mainshock fault plane parameters to vary modestly from the body-wave values and search for a second, predominantly strike-slip, subsidiary fault with as small a moment as possible that still adequately fits the GPS data. We have not done this search rigorously, but it appears possible to find a combination of faults such that the slip on the subsidiary fault is less than about 0.5 m, and its moment is about 25%-30% of the main shock moment. This is still larger than the 15% moment ratio estimated for the aftershocks, but it is within reasonable range. Given that the aftershock distribution shows clear evidence for rupture on the Harper fault as well as other sub-parallel faults, and perhaps also on the NNW-SSE structure defined by the aftershocks, we expect that a model that allowed slip on all these structures could be constructed to fit the GPS data with a moment ratio close to 15% without the necessity for invoking significant aseismic slip. Unfortunately, the complexity of the earthquake and the number of structures activated means that this supposition cannot be rigorously tested with the limited GPS data available.

A further note of caution in interpreting the GPS data is that the relatively large moment inferred for the subsidiary fault is dependent to some extent on the displacements at just two or three stations. Inspection of these sites a few weeks after the earthquake revealed no evidence for local ground instability, but since field evidence of displaced boulders indicates that accelerations in excess of 1 g occurred in the near field it remains a possibility that some of the closer GPS stations did suffer local disturbance as well as recording the regional deformation field from the earthquake.

Additional work on the geodetic inversions is expected to be done within the next year (under FRST funding).

Cass earthquake

The Cass earthquake occurred just outside the GPS network, but still sufficiently close to disturb a number of stations. Following the earthquake, eleven stations were resurveyed in early 1996. The displacement field, approximately corrected for interseismic displacement, between 1995 and 1996 is shown in Figure 4. Because the earthquake is outside the GPS network we only have displacement data from within one quadrant so we are unable to formally invert the geodetic data for information about the faulting. We can, however, compare the observed displacement field with dislocation forward-model predictions using both the body-wave mechanism solution and a fault plane that best fits the aftershock distribution [Gledhill et al., 1998]. Both models provide a reasonable fit to the observations and it is not possible to discriminate between them based on the limited geodetic data.

Arthurs Pass postseismic effects

The cross section in Figure 1b shows a subtle feature in the fault-normal velocity that we believe is due to post-seismic effects of the Arthur's Pass earthquake. The feature occurs above the down-dip end of the postulated fault plane (see Fig. 3) and has a pattern similar to that expected on theoretical grounds. Modelling of the postseismic displacements is planned, to derive information on the rheological properties at depth. But first a more rigorous treatment of the Cass coseismic effects is required, so that the interseismic velocity field can be estimated more reliably. A planned resurvey in the summer of 1999/2000 should also improve the interseismic velocity estimate (assuming we don't have yet another earthquake!).

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Publications resulting from this grant

Arnadottir, T., J. Beavan and C. Pearson, 1995. Deformation associated with the 18 June, 1994, Arthur's Pass earthquake, New Zealand, N. Z. J. Geol. Geophys., 38, 553-558.

Pearson, C., J. Beavan, D.J. Darby, G.H. Blick and R.I. Walcott, 1995. Strain distribution across the Australian-Pacific plate boundary in the central South Island, New Zealand, from 1992 GPS and earlier terrestrial observations, J. geophys. Res., 100:B11, 22,071-22,081.

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Arthur's Pass GPS network, 1995-1997

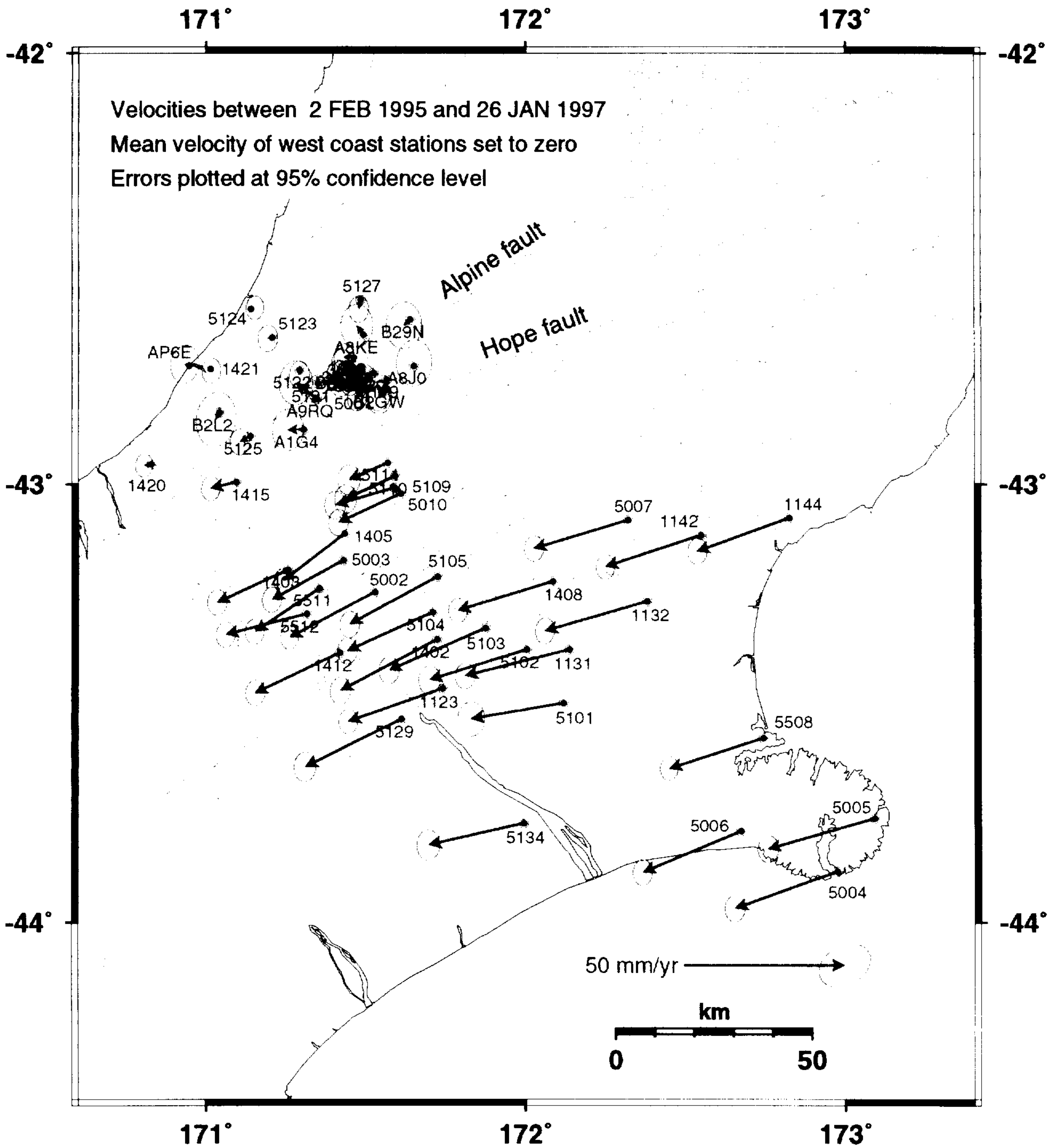

Figure 1a. 1995-97 velocities within the Christchurch-Hokitika GPS network. Points affected by Cass coseismic displacement and Arthur's Pass postseismic displacement are not shown. Faults shown are from the GNS Active Faults database.

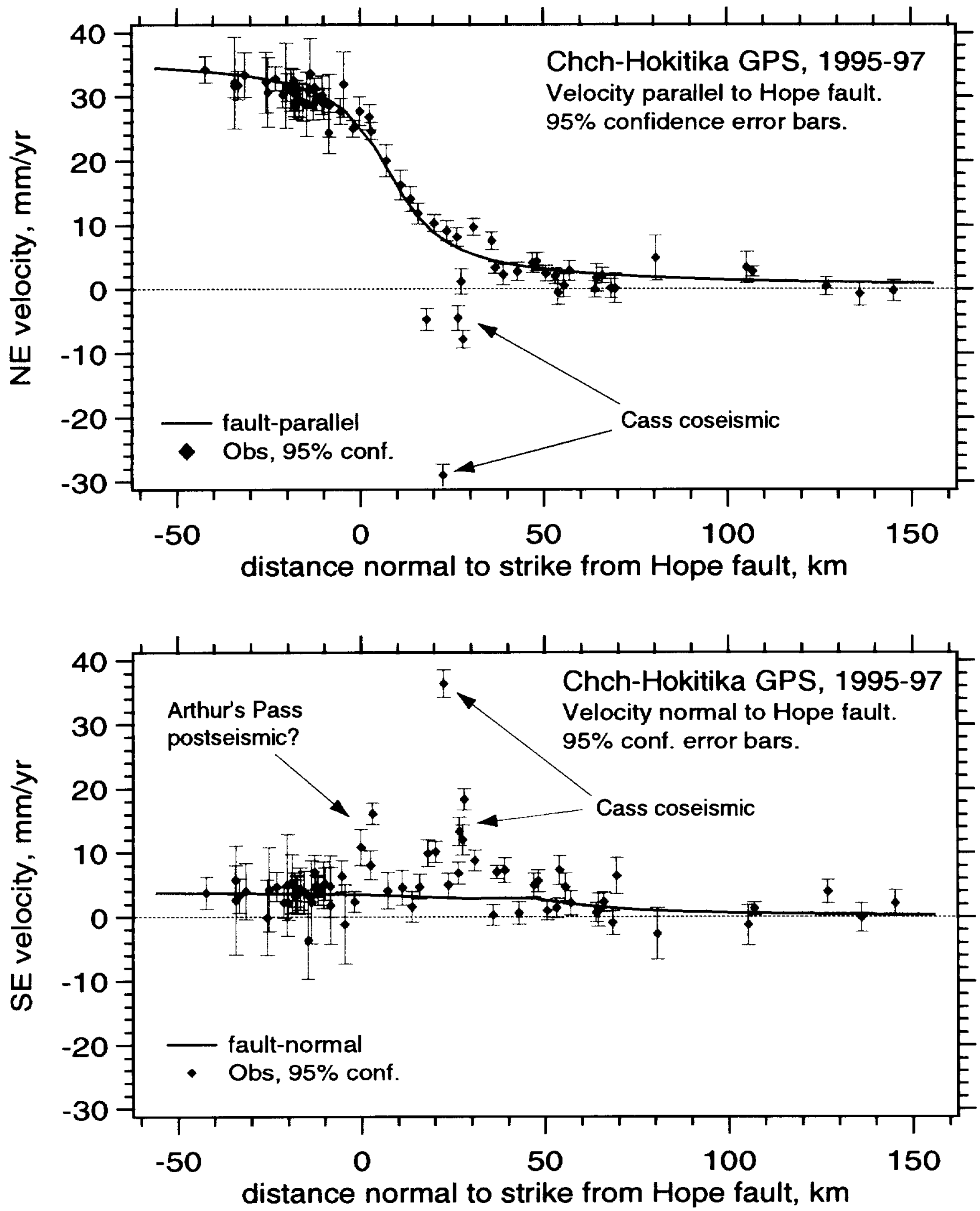

Figure 1b. Cross sections of velocity parallel and normal to the Hope fault. Note the obvious coseismic effects of the 1995 Cass earthquake, and the more subtle signal that we believe is a postseismic response following the 1994 Arthur's Pass earthquake.

Observed and Calculated Coseismic Displacements 1992 - 1995

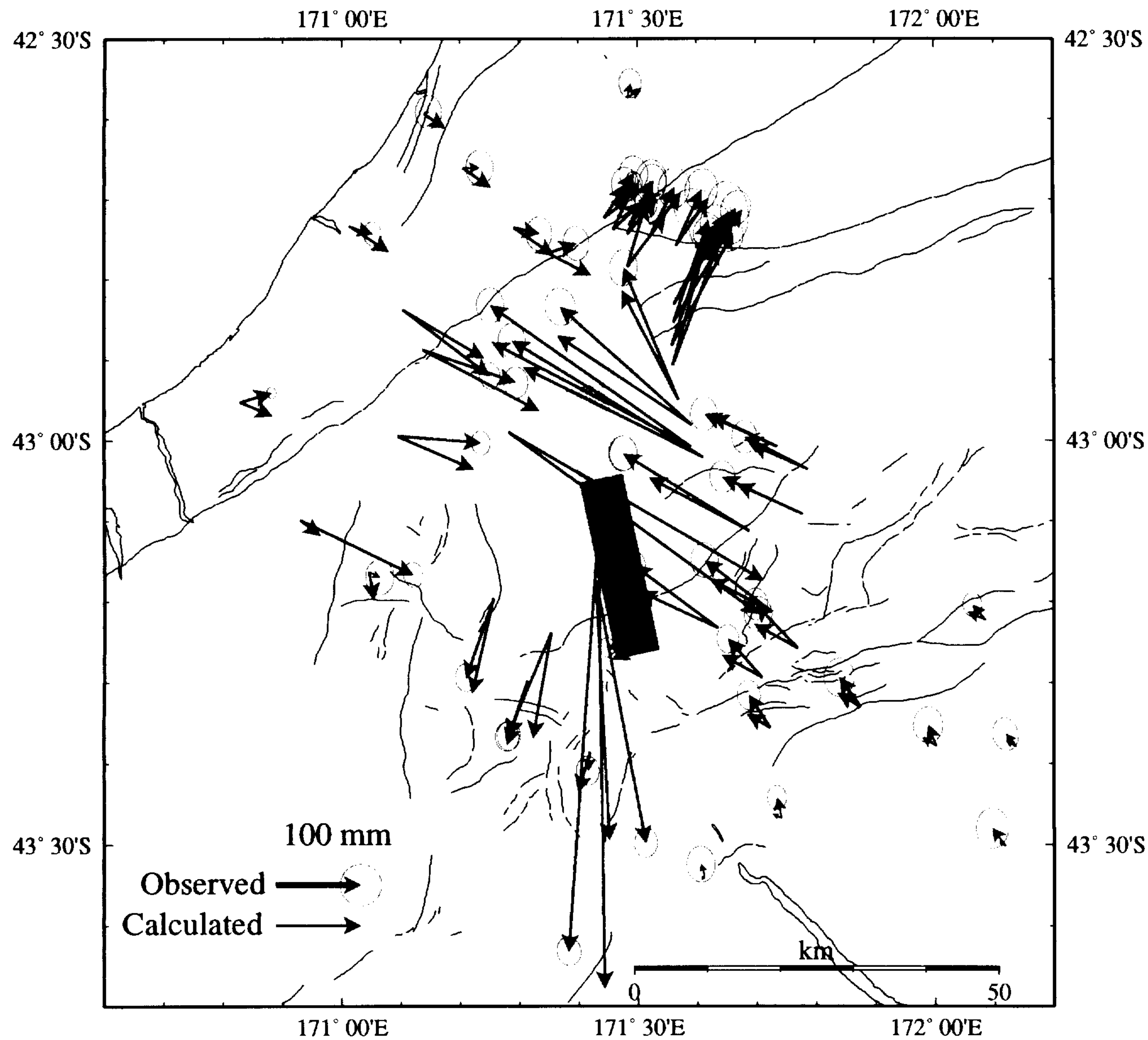

Figure 2. Best single-fault inversion for the Arthur's Pass earthquake from 1992-95 data, allowing two different slip patches on the fault plane. The solution is very similar to that ofArnadottir et al. [1995], who used 1992-94 data. The slip is a mixture of left-lateral and thrusting, and the northern third of the fault plane has an order of magnitude greater moment release than the southern two-thirds.

Best Fit Model Constrained by Body Wave Inversion

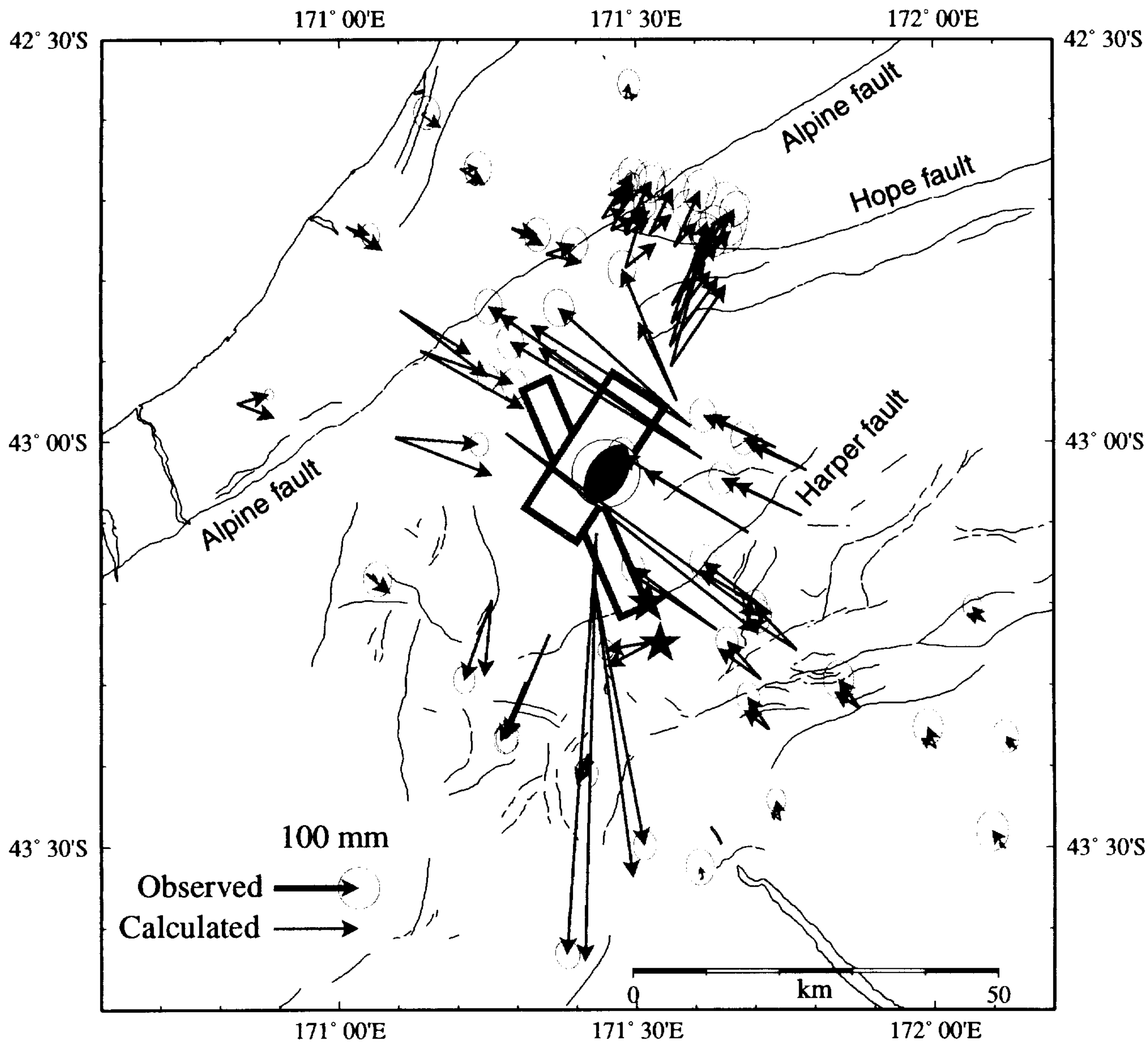

Figure 3. Best fitting two-fault model with one fault constrained to a thrust mechanism derived from body-wave modeling. The inversion requires almost as much moment release on the cross fault as on the NE-striking thrust [Arnadottir, 1995]. The stars are the locations of the two largest aftershocks, both of which had strike-slip mechanisms.

Cass 1995

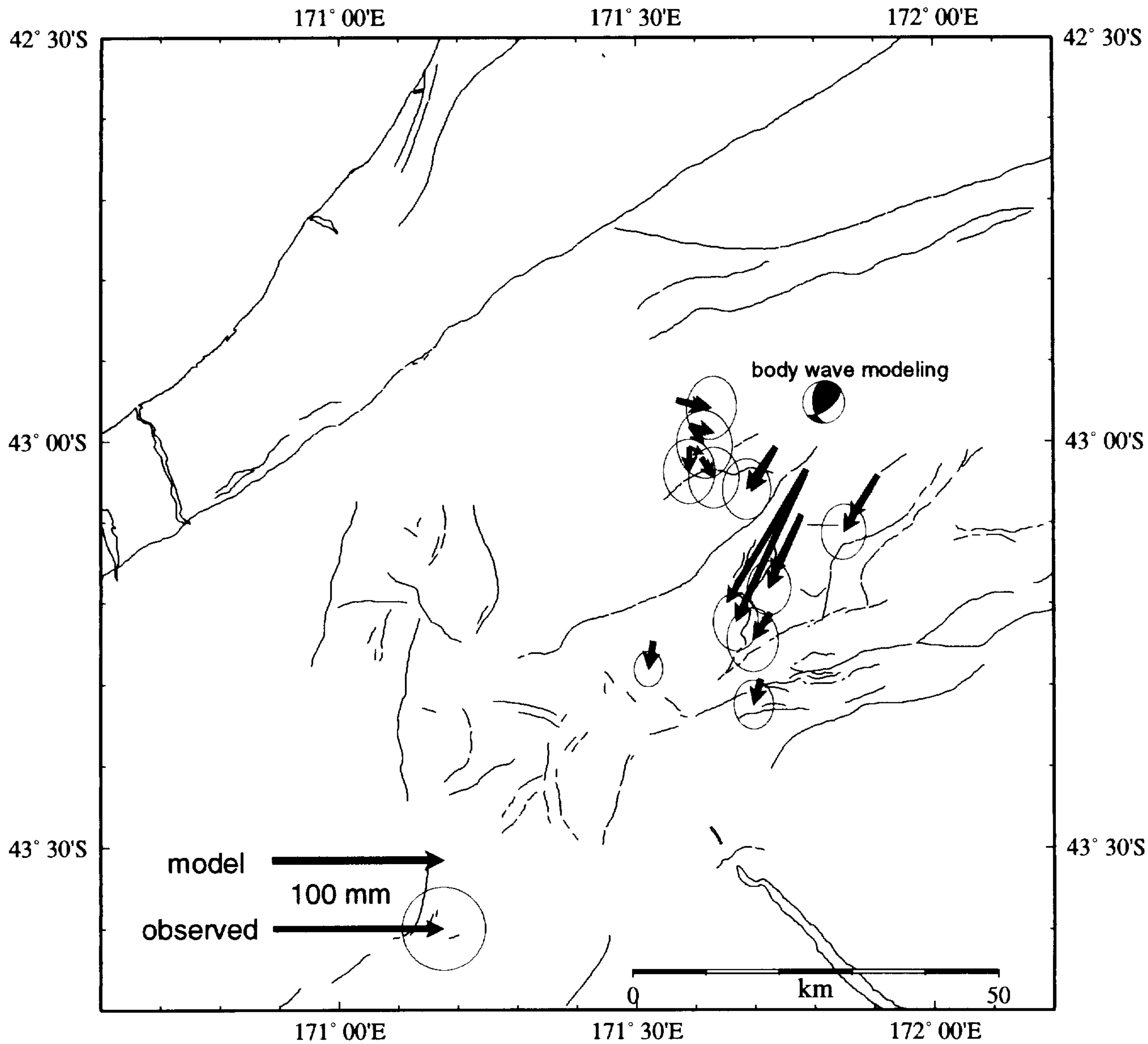

Figure 4. Coseismic displacements due to the 1995 Cass earthquake. A model based on the body-wave focal mechanism and a model based on the aftershock plane both give reasonable fits to the GPS displacement data.